Micromanipulation Using Squeeze Effect

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Abstract— In this paper, we proposed a novel strategy for pick and place operation in a micro range, by using a squeeze effect. In a micro range, the attracting forces such as the van der Waals, capillary, and electrostatic forces are dominate due to the scaling effect. The attracting forces make a release of an object difficult. In this paper, by vibrating the finger, we generate the gas film (the squeeze effect) between the object and the finger and relax the attracting forces. Some experimental results are shown to verify our approach.

I. INTRODUCTION

Recently, there has been a growing interest in a manipulation of a micro/nano sized object. It is the skill required to assemble or maintain microcomputers, micro electronics parts, a micro medical equipment, and so on. Different from a manipulation in a macro range, we cannot neglect the attracting force between a micro object and end effectors. In the macro range, the van der Waals, capillary, and electrostatic forces (proportional to surface area) become more significant than the inertial and gravitational forces (proportional to volume), because of the scale effect [1], [2]. The attracting force is resulted from the van der Waals, capillary, and electrostatic forces. Then, even in a basic operation such as pick and place, a release of an object is very difficult.

Many researchers have discussed how to release a micro object [3]–[9]. Arai et. al. [3] proposed an adhesion-type micro endeffector. There are micro holes on the endeffector. By controlling the pressure inside the holes by temperature, we can absorb and release a micro object. But it is hard to control the temperature because the temperature is influenced by an environment. Also treatable objects depend on the size of the holes. Zesch et. al. [4] developed a vacuum gripping tool consisting of a glass pipette and a computer controlled vacuum supply. But treatable objects depend on the size of the hole of the pipette. Rollot et. al. [5] proposed a method for pick and place of a micro spherical object when the endeffector has higher surface energy than the table (substrate). The problem is the release of the object. The release was done by slopping the endeffector. But the strategy can be applied to limited objects. Then, Haliyo et. al. [6], [7] proposed a strategy for the release, which is to vibrate the endeffector and give the micro object enough acceleration to remove from the endeffector. However, it is hard to control the motion of the object after the release and to preciously position the object. Saito et. al. [8] proposed a method for pick and place of a micro object under an SEM.

But, treatable objects are limited to a sphere. Saito et. al. [9] proposed a way for detachment of an adhering micro particle from a probe by controlling the electrostatic force. But, It is hard to control the motion of the object and to preciously position the object.

In this paper, we propose a novel way for pick and place operation in a micro range. The strategy is based on a squeeze effect [10], [11]. The squeeze effect is a phenomenon of tribology/lubrication. When the distance between the two surfaces is very small and one/both of the surfaces moves vertically to the surfaces, a pressure causes between the surfaces. The pressure can relax the attracting forces. By using this phenomenon, we propose a novel method for manipulation. This method can provide a precious operation. Also, the strategy can be applied to any arbitrary shaped object and can be simply constructed.

This paper is organized as follows. At first, the target system is shown. Next, we describe about the reduction of attracting forces. Then, we propose a novel way for pick and place in a micro world. Finally experimental results are presented in order to show the validity of our approach.

II. TARGET SYSTEM

The target system is shown in Fig.1. In this paper, we consider a pick and place operation of a micro object in a planner space (a gravity force doesn't work). The operation is done by a gripper constructed by a pushing finger and a support finger. The pushing finger plays a role of pushing the mico object toward the support finger/a substrate. The support finger plays a role of supporting the mico object against the pushing forces from the pushing finger. Using these fingers, we consider picking and placing a spherical object on the substrate. For the simplicity, we deal with a spherical object, but the proposing strategy can be applied to other shaped objects.

A. Experimental set up

Fig.2 shows the experimental set up. This system consists of the manipulation system, the image-capturing system, and the finger-oscillating system. The manipulation system consists of the pushing finger, the support finger, the substrate, and the object. The pushing and support fingers are copper cuts in size of $45\times3\times0.3$mm (see Fig.3). On the pushing finger, the piezocell (FUJI CERAMICS, Z0.2T50$\times$50$\times$50S-W C6) of $4\times3\times0.3$mm is bonded as an actuator for oscillating it. These fingers are attached

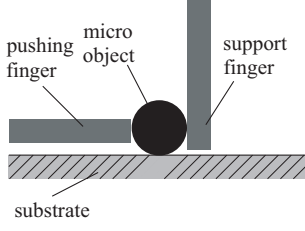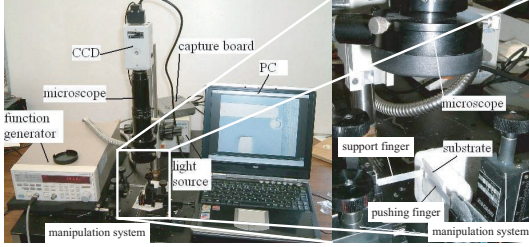Fig. 1.   Target System

Fig. 2.   Experimental set up
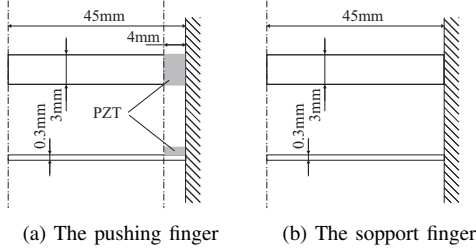

(a) The pushing finger   (b) The sopport finger

Fig. 3.   Overview of the fingers

(a) Case I   (b) Case II

Fig. 4.   Two cases for analysis

Fig. 5.   Model for analysis of squeeze effect

with the three-dimensional manipulator (NARISHIGE, M-152). The substrate is also a copper cut. The fingers and the substrate are grounded for preventing an extra charge. The object is a glass sphere (UNION, unibeads) with a radius of $100[\mu\text{m}]$. The image-capturing system is for recording the movie of the manipulation. The manipulation is captured by the CCD camera (IAI, CV-S3200) through the microscope (MORITEX, ML-Z07545). The captured data is send to PC through the capture board (V-STREAM, VS-TV2800R). The oscillation of the pushing finger is generated by oscillating the piezocell by the function generator (YOKOGAWA, FG120) through the power amplifier (NF, 4010).

III. REDUCTION OF ATTRACTING FORCES

In this section, we present a novel way for reducing the attracting forces between the object and the finger.

For the pick and place operation, we consider reducing the attracting forces which work between the pushing finger and the object in the two cases shown in Fig.4. By not oscillating the finger in contact with the object but making the oscillating finger contact with the object, we reduce the attracting forces. Note that the distance between the finger and the object is very small. In this case, we can take the following advantages; (1) The squeeze effect is caused and a pressure between the finger and the object is generated. The pressure can reduce the attracting forces between the
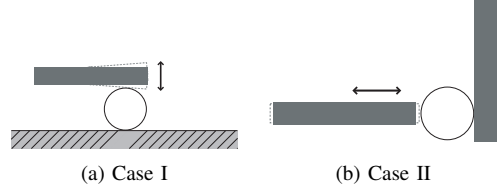
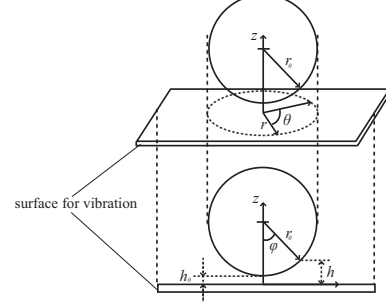finger and the object. (2) The acceleration is generated at the tip of the finger and the acceleration can counteract the attracting forces. In the following, we address the detail of the above two phenomena and the attracting forces in the case where the oscillated pushing finger just comes into contact with the object and any adhesions don't still occur, and then we show that the two phenomena is effective for reducing the attracting forces.

A. Squeeze Effect

In this subsection, we describe the squeeze effect [11]. Here, we consider generating a gas film between the tip of the finger and the spherical object. For the simplicity, we regard the tip of the fingers as a surface and the surface is assumed to be oscillated sinusoidally in a vertical direction to the surface (see Fig.5). We make the following assumption; (1) The flow is Newtorian, isothermal, and a compressible perfect gas, (2) The inertia effect of the flow is negligible, (3) The sphere (object) is in stationary state.

In this case, the flow is governed by the following generalized Reynolds equation [12];

$$\frac{1}{R}\frac{\partial}{\partial R}(\bar{Q}_p PH^3 R \frac{\partial P}{\partial R}) + \frac{1}{R^2}\frac{\partial}{\partial \Theta}(\bar{Q}_p PH^3 \frac{\partial P}{\partial \Theta})$$
$$= \sigma\frac{\partial(PH)}{\partial T} + \Lambda\frac{\partial(PH)}{\partial \Theta} \qquad (1)$$

where R: normalized r coordinate ($= r/r_0$ where r_0 denotes the representative length (the radius of the sphere)), Θ: normalized θ coordinate, T: normalized t (time) ($= \omega t$ where ω denotes the frequency of the oscillation), P: normalized pressure ($= p/p_a$ where p denotes the pressure and p_a denotes the atmospheric pressure), H: normalized thickness between the surface and the object ($= h/h_r$ where $h_r(= r_0)$ denotes the representative length), σ: squeeze number ($=12\mu\omega/p_a$ where μ denotes the viscosity of the gas), Λ: bearing number ($=6\mu U/p_a h_r$

where U denotes the relative rotational velocity between the surface and the sphere).

Note that this equation (1) is expressed by cylindrical coordinates (Fig.5). The flow of gas is characterized by Knudsen number K_n ($= \lambda/h$ where λ denotes the molecular mean free path). The equation (1) was derived based on the Boltzman equation in order to deal with a ultra-thin gas film whose Knudsen number is large [12]. Note that the equation (1) is originally for large Knudsen numbers but valid for arbitrary Knudsen numbers.

In the equation (1),

$$\bar{Q}_p = Q_p(D, \alpha)/Q_{con}(D), \quad Q_{con}(D) = D/6 \quad (2)$$

where $Q_p(D, \alpha)$ is a Poiseuille flow rate coefficient, $Q_{con}(D)$ is the coefficient for continuous flow, D is an inverse Knudsen number, and α is a reflection coefficient. D is expressed by

$$D = D_0 PH, \quad D_0 = p_a h_r/\mu\sqrt{2\mathcal{R}\mathcal{T}} \quad (3)$$

where $\mathcal{R}$ denotes the gas constant and $\mathcal{T}$ denotes the temperature. It is hard to calculate $\bar{Q}_p$ and then a data base of $\bar{Q}_p$ was made for easy calculation [13].

Considering the symmetry of the system, Equation (1) can be reduced to

$$\frac{1}{R}\frac{\partial}{\partial R}\{\bar{Q}_p PH^3 R\frac{\partial P}{\partial R}\} = \sigma\frac{\partial(PH)}{\partial T}. \quad (4)$$

In a micro range, the elastic deformation of the materials cannot be negligible. Then, we consider the elastic deformation of the surface and the object. In this case, the thickness of the film is given by [14]

$$h = h_0 + \delta h \cos\omega t + r^2/(2r_0) + \lambda(p, r) \quad (5)$$

where δh denotes the amplitude of the oscillation and

$$\lambda(p, r) = -\frac{2}{\pi E'}\int p(x)\log((r-x)^2)dx + \text{const} \quad (6)$$
$$2/E' = (1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2$$

where E_i and ν_i ($i = 1, 2$), respectively, Young's modulus and Poisson's rate of the surface ($i = 1$) and the object ($i = 2$). If we normalize h with respect to $h_r (= r_0)$, the normalized thickness of the film is expressed by

$$H = H_0 + \delta H \cos T + R^2/2 + \Lambda(P, R) \quad (7)$$

where $H_0 = h_0/h_r$, $\delta H = \delta h/h_r$, and $\Lambda(P, R)$ is a normalized $\lambda(p, r)$.

The boundary conditions with respect to $P(R, T)$ are; a) $P(1, T) = 1$: The pressure at the periphery is p_a at all times. b) $\frac{\partial P(0, T)}{\partial R} = 0$: The slope of the pressure profile at the center is zero at all times.

Solving (4) for P subject to (7) and the above boundary conditions, the pressure exerted on the surface and the object at time T is expressed by
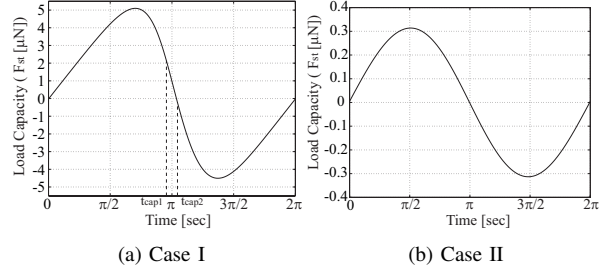
$$P_s(R, T) = P(R, T) - 1. \quad (8)$$

(a) Case I (b) Case II

Fig. 6. Transition of the load capacity

TABLE I
LIST OF PARAMETERS

Young's modulus (Cu)	E_1	12.3 [10^4MPa]
Young's modulus (glass)	E_2	7.5 [10^4MPa]
Young's modulus (Cu)	ν_1	0.35 [-]
Young's modulus (glass)	ν_2	0.17 [-]
radius of the sphere	r_0	100 [μm]
amplitude of the oscillation (Case I/Case II)	δh	0.17/0.024 [μm]
roughness (Case I/Case II)	h_b	0.05/0.5 [μm]
atmospheric pressure	p_a	0.1 [MPa]
viscosity of the gas	μ	18.6[μPa s]
frequency of the oscillation	$\omega/2\pi$	4.088 [kHz]

Then, the squeeze force at time T is expressed by

$$F_{st}(T) = \int_0^{2\pi}\int_0^1 P_s(R, T)R\, dRd\Theta$$
$$= 2\pi\int_0^1 R(P(R, T) - 1)\, dR. \quad (9)$$

Then, the mean squeeze force is expressed by

$$f_{st} = (p_a r_0^2)\frac{1}{2\pi}\int_0^{2\pi} F_{st}(T)\, dT$$
$$= p_a r_0^2\int_0^{2\pi}\int_0^1 R(P(R, T) - 1)\, dRdT. \quad (10)$$

Using the parameters shown in Table.I, we compute the pressure profile of the squeeze film. We measured the displacement of the oscillating finger by the laser displacement meter (SONY, VL10). The frequency of the oscillation is set to 4.088[kHz]. The input signal is set to a sine curve. The voltage of the amplitude of the input signal is set to 10 [V] for Case I and 30 [V] for Case II. We also measured the roughness (arithmetic average roughness (R_a)) of the contact surface of the pushing finger by surfcom120A (tokyo seimitsu). The values of the amplitude and the roughness in Table.I are the measured values. Note that we set $h_0 = \delta h + h_b$. Namely, we consider the case where the pushing finger just comes into contact with the object. We applied Newton-Raphson method to finite difference representations of (4) and (7).

The results about load capacity given by (9) are shown in Fig.6. The average of load capacity per one cycle (given by (10)) was 0.16[μN] in Case I and 0.55[nN] in Case II.
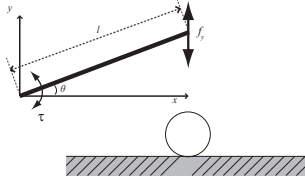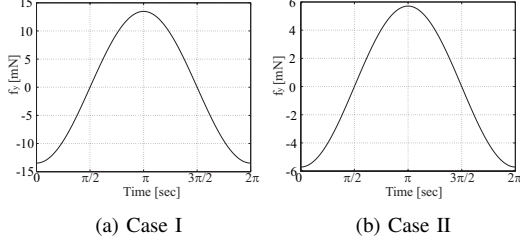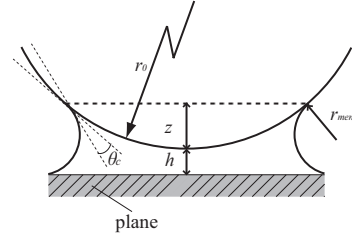
Fig. 7.   The vibration of the finger

(a) Case I   (b) Case II

Fig. 8.   Trajectory of f_y

Fig. 9.   Interaction between sphere and plane
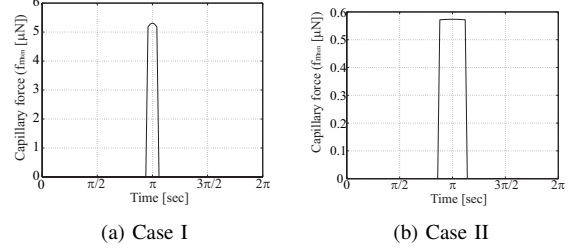

(a) Case I   (b) Case II

Fig. 10.   Profile of the capillary force

B. the accelerarion of the tip of the finger

In this subsection, we cosider the accelerarion of the tip of the pushing finger without considering the effect of the squeeze film. For the simplicity, we consider the motion of the pushing finger in a planar space (for Case I, see Fig.7). Let θ be the angle between the figner and the x axis. Let τ be the joint driving torque (applied by the piezocell). Then, the equation of motion of the finger is given by $\tau = I\ddot{\theta}$ where I denotes the inertia moment with respect to the proximal end of the finger. Letting l be the length of the finger, the tip position of the finger is given by $\begin{pmatrix} x_t & y_t \end{pmatrix}^T = \begin{pmatrix} l\cos(\theta) & l\sin(\theta) \end{pmatrix}^T$. If θ is very small, $\begin{pmatrix} x_t & y_t \end{pmatrix}^T = \begin{pmatrix} l & l\theta \end{pmatrix}^T$. Then, the (inertial) force equivalent to the joint torque τ, which works at the tip of the finger in y direction, is given by

$$f_y = I\ddot{y}/l^2. \qquad (11)$$

Now, we oscillate the tip of the finger with the frequency and the amplitude shown in Table.I. Then, y_t can be written as follows;

$$\ddot{y}_t = -(\delta h)\omega^2 \cos(\omega t). \qquad (12)$$

From (11) and (12), we get

$$f_y = -I(\delta h)\omega^2 \cos(\omega t)/l^2. \qquad (13)$$

Using similar formulation, f_y for Case II is given by

$$f_y = -m(\delta h)\omega^2 \cos(\omega t). \qquad (14)$$

Substituing the values in Table.I and Fig.3 into (13) and (14), we get the trajectory of f_y (See Fig.8).

C. Attracting Forces

The attracting forces cause due to the van der Waals, capillary, and electrostatic forces [1], [2], [5], [15]. Among the three forces, capillary force is largest and is very large compared with the other forces. Then, in this paper, we consider only capillary force. The capillary force, interacting between a sphere and a plane, is expressed by [1], [2], [5], [15]

$$f_{ten} = (4\pi\gamma r_0 \cos\theta_c)/(1 + h/b) \qquad (15)$$

where γ denotes the surface tension (73×10^{-3}[N/m] for water), r_0 denotes the radius of the sphere, θ_c denotes the contact angle of a liquid on the surface, h denotes the distance between the surface of the sphere and that of the plane, b denotes the immersion height ($b = 2r_{men}$ where r_{men} is a meniscus curvature radius. r_{men} =1.6 [nm] for 50% relative humidity) (See Fig.9). Note that if $h \to 0$ and $\theta_c \to 0$, equation (15) becomes $f_{ten} = 4\pi\gamma r$.

The thickness of the liquid bridge which causes a capillary force is about 3[nm]. Then, we assume that the capillary force works when the distance between the object and the finger is under 3[nm]. Let t_{cap1} and t_{cap2} ($t_{cap2} > t_{cap1}$) be the times when the distance between the surface and the object $h_d (= h(r,t) - h_b = h(1,t) - h_b)$ is 3[nm]. Considering the roughness of the surface and using h given by (5), we calculate the capillary force. The results are shown in Fig.10.

The mean capillary force per one cycle is expressed by

$$f_{m_{ten}} = 1/2\pi \int_{t_{cap1}}^{t_{cap2}} \frac{4\pi\gamma r_0 \cos\theta_c}{1 + h(t)/b} dt. \qquad (16)$$

We obtained $f_{m_{ten}}$ = 0.26 [μN] in Case I and $f_{m_{ten}}$ = 0.075 [μN] in Case II.

D. Discussion

Based on the above analysis, we consider the reduction of the attracting forces. For the simplicity, we consider the case where the oscillated pushing finger just comes into contact with the object and any adhesions don't still occur.

At first, we consider Case I. In this case, the average of the squeeze force (0.16 [μN]) is approximately same as that of the capillary force (0.26 [μN]). Then, we believe that the squeeze force can almost counteract the capillary force that

works between the pushing finger and the object ($f_{t_{p-o}}$). In addition, from Fig.10(a), we can see that the $f_{t_{p-o}}$ itself is reduced (note that when there is no oscillation (and the pushing finger contacts the object), the magnitude of $f_{t_{p-o}}$ is always the maximum value shown in Fig.10(a)).

If we analyze from the local viewpoint, from Fig.6(a) and Fig.10(a), we can see that $f_{t_{p-o}}$ is reduced by the squeeze force in the almost all cases where $f_{t_{p-o}}$ works. When the squeeze force cannot reduce $f_{t_{p-o}}$, $f_{t_{p-o}}$ itself is reduced for an increase of the thickness (h). When there is no oscillation, $f_{t_{p-o}}$ is same as the capillary force that works between the substrate and the object ($f_{t_{su-o}}$) because both the roughnesses of the contact surfaces are same (we use the same part of the copper cut as the contact surface). Then, we think that $f_{t_{p-o}}$ is smaller than $f_{t_{su-o}}$. On the other hand, from Fig.8(a) and Fig.10(a), we can see that the very large (inertial) force at the tip of the pushing finger (f_y) works compared with $f_{t_{p-o}}$ when $f_{t_{p-o}}$ works. Then, we believe that $f_{t_{p-o}}$ can be completely counteracted by f_y (note that $f_{t_{p-o}} < f_{t_{su-o}}$).

Next, we consider Case II. In this case, we cannot get enough large squeeze force (0.55[nN]) to reduce $f_{t_{p-o}}$ (0.075 [μN]). However, from Fig.10(a), we can see that $f_{t_{p-o}}$ itself is reduced. In addition, even in the case where there is no oscillation, $f_{t_{p-o}}$ is smaller than the capillary force that works between the support finger and the object ($f_{t_{s-o}}$) because the roughness of the contact surface of the support finger is smaller than that of the pushing finger (see Table.I).

If we analyze from the local viewpoint, from Fig.8(b) and Fig.10(b), we can see that very large f_y works compared with $f_{t_{p-o}}$ when $f_{t_{p-o}}$ works. Then, we believe that $f_{t_{p-o}}$ can be completely counteracted by f_y (note that $f_{t_{p-o}} < f_{t_{s-o}}$).

If we summarize, we believe that in the both cases, if we make the oscillating pushing finger contact with the object, the attracting force is always counteracted, namely adhesions don't occur, and it is easy to remove the finger from the object. Note that if a decrease of h (δh) for the contact isn't large, we think a similar analysis can be valid and similar results can be obtained (note that an increase of h (δh) makes the squeeze force and f_y increase). But the detail analysis is our future work. Note also that if we oscillate the pushing finger in contact with the object, the above analysis cannot become valid because the profile of the oscillation is absolutely different and $f_{t_{p-o}}$ always works.

E. Confirmation of reduction of the attracting forces

Based on the above analysis, we do simple experiments in order to confirm whether it is easy to release the object or not. In this paper, we pay attention to the friction at the contact surface between the pushing finger and the object. If the attracting forces are reduced, the total force exerted on the contact surface becomes smaller and the sliding at the contact surface becomes easy to occur. Then, we investigate the friction at the contact surface by making the finger slide on the object. If the sliding is smooth, it means
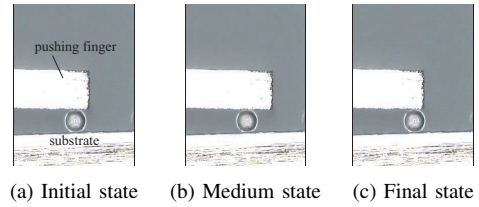

(a) Initial state   (b) Medium state   (c) Final state

Fig. 11. Confirmation of reduction of the attracting forces in Case I

(a) Initial state   (b) Medium state   (c) Final state
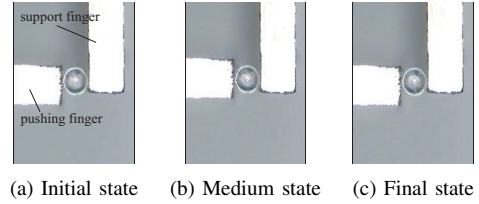
Fig. 12. Confirmation of reduction of the attracting forces in Case II

the attracting forces are enough reduced. If the sliding is hard to occur, it means the attracting forces aren't enough reduced and it is hard for the finger to release the object. At first, we placed the object on the substrate and made the oscillating finger contact with the upper side of the object (Case I). Then, we slid the finger on the object (Fig.11). The frequency of the oscillation was set to 4.088[kHz]. This frequency corresponds to the 4th mode of the finger. The input signal was a sine curve. We investigated the cases where the voltage of the amplitude of the input signal is 0, 10, 20, 30[V]. In the case where the voltage was 0[V], The object rotated and the finger didn't slide on the object. In the case where the voltage was larger than or equal to 10[V], the finger slid on the object. Fig.11 shows the case where the voltage is 10[V]. From these results, the attracting forces can be enough reduced in the case where the voltage is larger than or equal to 10[V].

We also investigated in Case II (Fig.12). At first, we placed the object on the support finger and made the oscillating finger contact with the left side of the object. Then, we slid the finger on the object (Fig.12). The frequency of the oscillation was set to 4.088[kHz]. The input signal was a sine curve. We investigated the cases where the voltage of the amplitude of the input signal is 0, 30, 35, and 40[V]. In the case where the voltage was 0[V], The object rotated and the finger didn't slide on the object. In the case where the voltage was larger than or equal to 30[V], the finger slid on the object. Fig.11 shows the case where the voltage is 30[V]. From these results, the attracting forces can be enough reduced in the case where the voltage is larger than or equal to 30[V].

IV. STRATEGY FOR PICK AND PLACE OPERATION IN A MICRO RANGE

Based on the above analysis and the experimental results, we propose a novel strategy for pick and place operation in a micro range.

The procedure of the strategy is as follows (Fig.13):
(1) This is the initial state. (2) Make the support finger contact with the object on the substrate. (3) Make the
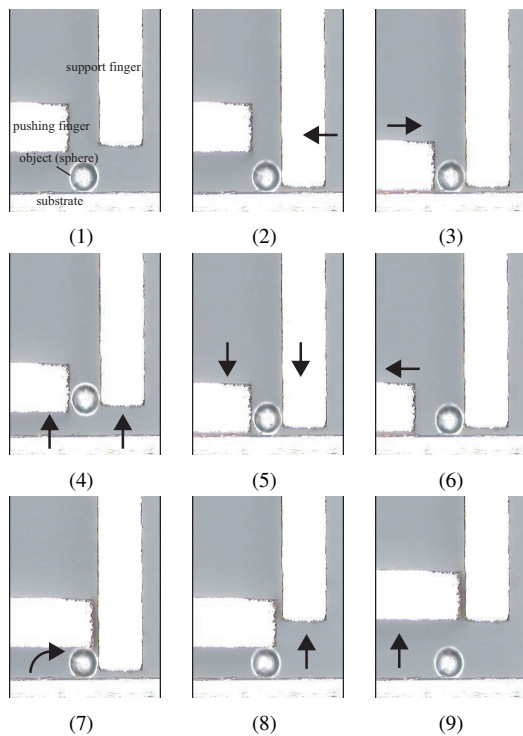
Fig. 13. Pick and place operation

oscillating pushing finger contact with the object on the substrate from the left side. (4) Pick the object by moving the pushing and support fingers upward. (5) Place the object by moving the pushing and support fingers downward. (6) Remove the pushing finger from the object. (7) Make the oscillating pushing finger contact with the upper side of the object. (8) Remove the support finger from the object by moving it upward. (9) Remove the pushing finger from the object by moving it upward.

Note that in the procedure (6) and (9), we can easily remove the pushing finger for the oscillation of the finger (squeeze effect), which relaxes the attracting forces.

The experimental results are shown in Fig.13. The frequency of the oscillation of the pushing finger was set to 4.088[kHz]. The input signal for the oscillation was a sine curve and the voltage of its amplitude was set to 30[V] in the procedure (3) ~ (6), and to 10[V] in the procedure (7) ~ (9). This setting is based on the above analysis and the experimental results. From Fig.13, it is clear that the pick and place operation was done successfully. We did this operation several times. We succeeded every time. We also did this procedure without the oscillation of the pushing finger. In this case, the attracting forces interfered and the operation resulted in fail (for example, in the procedure (9), the object removed from the substrate for the attracting forces). Also, we tried to take this strategy with other materials: aluminium for the two fingers and polystyrene for the substrate (the object is the same material). The operation was also done successfully in this case.

V. CONCLUSION

In this paper, we proposed a novel strategy for pick and place operation in a micro range. In a micro range, the attracting forces such as the van der Waals, capillary, and electrostatic forces become dominate due to the scaling effect. The attracting forces make a manipulation of an object difficult. In this paper, by vibrating the finger, we generated the squeeze film between the object and the finger. We showed the squeeze film can make the attracting forces relaxed and the manipulation of the object easy. We proposed a strategy for pick and place operation using the squeeze film. This strategy can be applied to any arbitrary shaped object and give a precious manipulation. The architecture of the strategy is very simple and can be embedded into a conventional end-effecter. The experimental results showed the effectiveness of our approach.

REFERENCES

[1] R. S. Fearing, "Survey of sticking effects for micro-parts," *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 212–217, 1995.

[2] F. Arai, D. Andou, and T. Fukuda, "Micro Manipulation Based on Physical Phenomena in Micro World (1st Report, The Reduction Method of Van Der Waals Force)," *Transactions of the Japan Society of Mechanical Engineers, Series C*, vol. 62, no. 603, pp. 4286–4293, 1996, (in Japanese).

[3] F. Arai, D. Andou, Y. Nonoda, and T. Fukuda, "Micro Manipulation Based on Physical Phenomena in Micro World (Principle and Prototype Experiments of Adhesion-type Micro Endeffector)," *Transactions of the Japan Society of Mechanical Engineers, Series C*, vol. 62, no. 604, pp. 4630–4635, 1996, (in Japanese).

[4] W. Zesch, M. Brunner, and A. Weber, "Vacuum tool for handling micro objects with a nano robot," *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 1761–1766, 1997.

[5] Y. Rollot, S. Régnier, and J. Guinot, "Dynamical model for the micro-manipulation by adhesion : Experimental validations for determined conditions," *Journal of Micromechatronics*, vol. 1, no. 4, pp. 273–297, 2002.

[6] D. S. Haliyo, Y. Rollot, and S. Régnier, "Manipulation of micro-objects using adhesion forces and dynamical effects," *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 1949–1954, 2002.

[7] D. S. Haliyo and S. Régnier, "Advanced applications using [mü]mad, the adhesion based dynamic micro-manipulator," *Proc. of the IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics*, pp. 880–885, 2003.

[8] S. Saito, H. T. Miyazaki, T. Sato, K. Takahashi, and T. Onzawa, "Analysis of micro-object operation based on the dynamics considering the adhesion under an SEM," *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 1349–1357, 2001.

[9] S. Saito, H. Himeno, and K. Takahashi, "Electrostatic detachment of an adhering particle from a micromanipulated probe," *Journal of Applied Physics*, vol. 93, no. 4, pp. 2219–2224, 2003.

[10] T. Watanabe and S. Fukui, "A method for controlling tactile sensation of surface roughness using ultrasonic vibration," *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 1134–1139, 1995.

[11] E. O. J. Salbu, "Compressible squeeze films and squeeze bearings," *Transaction of the ASME, Journal of Basic Engineering*, vol. 86, pp. 355–366, 1964.

[12] S. Fukui and R. Kaneko, "Analysis of ultra-thin gas film lubrication based on linearized boltzmann equation: First report-derivation of a generalized lubrication equation including thermal creep flow," *Transaction of the ASME, Journal of Tribology*, vol. 110, pp. 253–262, 1988.

[13] ——, "A database for interpolation of poiseuille flow rates for high knudsen number lubrication problems," *Transaction of the ASME, Journal of Tribology*, vol. 112, pp. 78–83, 1990.

[14] Y. Yamamoto and M. Kaneda, *Tribology*. Rikogakusya, 1998, (in Japanese).

[15] J. N. Israelachvili, *Intermolecular and Surface Forces, 2nd ed.* Academic, New York, 1992.